NAT'L INST. OF STAND & TECH
A11106 685531

A TUBULAR ELECTRODYNAMOMETER FOR HEAVY CURRENTS

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1. THEORY OF INSTRUMENT

To obtain the same current distribution for both alternating and direct current it is usual to strand the windings of the field coils of electrodynamometers, and the strands should also be throughly mixed, so that all shall have the same effective resistance and inductance. For very heavy currents this becomes a matter of extreme difficulty.

In the present instrument an entirely different means of obtaining the same end is employed. Evidently the ultimate requisite in an instrument for transferring from alternating to direct current is that the torque shall be the same, and it is immaterial whether we make the current distribution the same, or the field due to the current the same. The latter is the method adopted. There is no theoretical reason why the current distribution and the magnetic field could not both be allowed to vary if it could be shown that the torque did not change.

The field "coil" of the instrument consists of two coaxial copper tubes, thus giving a circular magnetic field in the space between the tubes. On direct current the distribution may be assumed to be uniform over the cross section of the tubes, but on alternating current, as is well known, the stream lines are crowded toward the

outside of the inside tube and toward the inside of the outside tube, and the amount of this change depends upon the frequency. But it may easily be shown that if we have axial symmetry the magnetic field at any point is independent of the current distribution. Expressed in the usual terms there is no magnetic field between the tubes due to the outside tube, and that due to the inside tube is independent of the skin effect, but it is better to consider the arrangement as a special case of a more general principle.

Let us consider a generalized toroid such as would be formed by rotating any closed circuit, such as A (Fig. 1) about an axis. We may think of the circuit A as consisting of a wire carrying a current, and similarly of the surface of revolution as being a current sheet; or we may think of the surface as being wound with a layer of wire with no space between turns and thus becoming an endless solenoid.

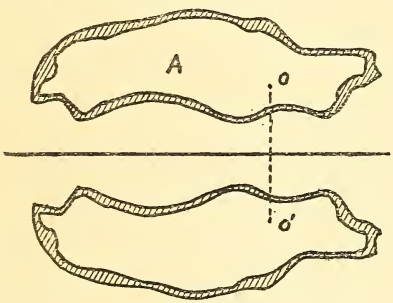

Fig. 1.—*Generalized toroid.*

It has been shown by Maxwell[1] and by Gray[2] that the field at any point, as at O, is independent of the size, shape, and thickness of the conductor and depends only on the total current and the distance of the point from the axis. This may be shown by a very simple process of reasoning. The all-important condition is axial symmetry.

Consider a circle perpendicular to the plane of the paper, and cutting it in the points O and O'. This circle links once with the current. Hence, the line integral of the magnetic field around this circle, or the work required to carry a unit pole around it, is 4π times the total current, or if we remember that H is uniform around the circle.

$$2\pi R H = 4\pi I$$
$$H = 2I/R$$

The value of H at any point within is thus entirely independent of the dimensions of the conductor, provided there is axial sym-

[1] Electricity and Magnetism, Vol. II, art. 681. [2] Absolute Measurements, Vol. II, p. 278.

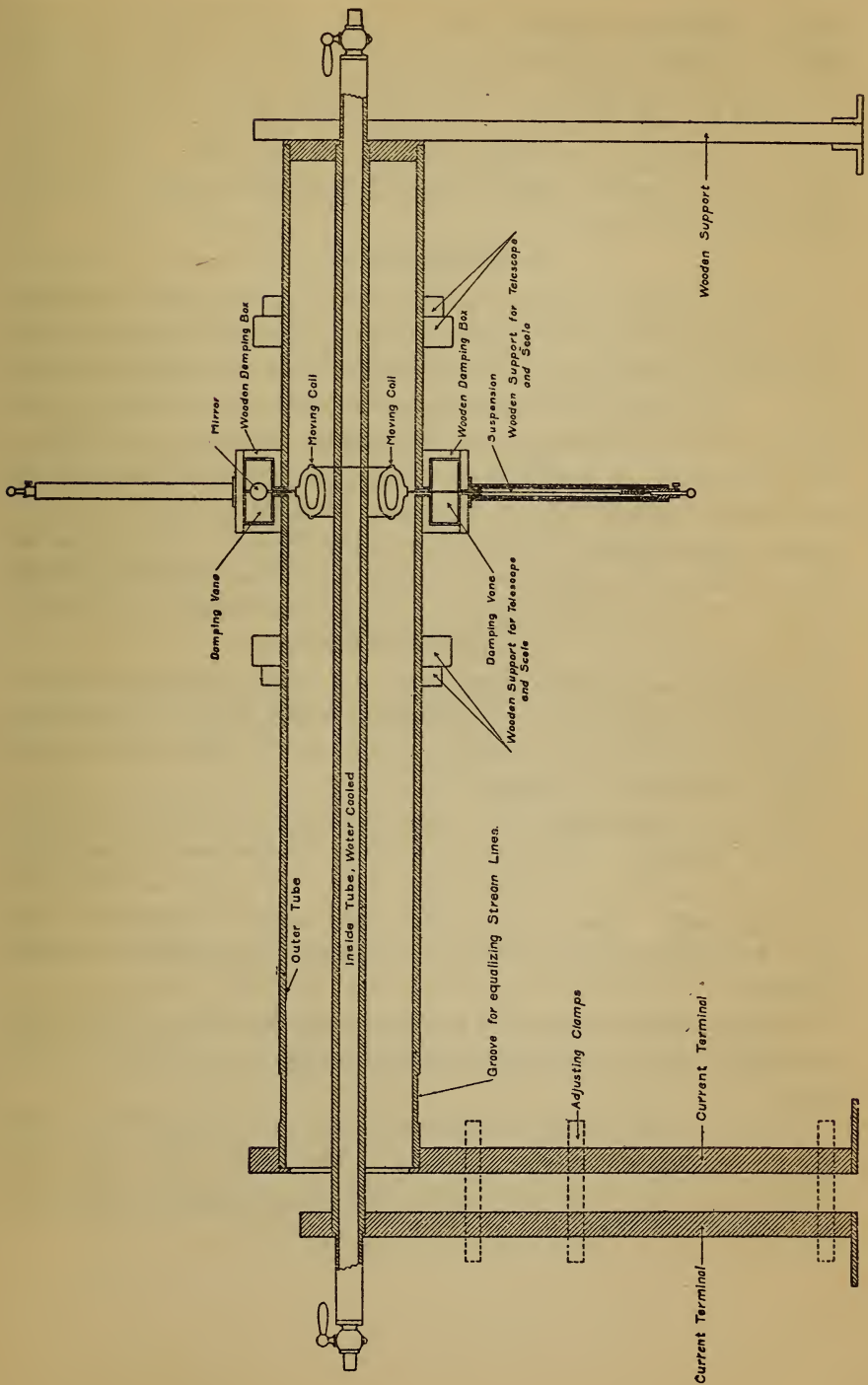

Fig. 2.—*Tubular electrodynamometer vertical section.*

metry. Hence, an approximation to such a form for the current coils is admirably adapted for alternating-direct-current transfer dynamometers, since it is independent of the current distribution.[3]

It will be seen that the concentric tubes form an approximation to a toroid or an endless solenoid of one turn. It can only be an approximation, since it must be open at one end in order to introduce the current.

2. CONSTRUCTION

The instrument was built in the instrument shop at the Bureau of Standards by Mr. G. C. Klein. Fig. 2, which is a vertical longitudinal section through the instrument, shows the general arrangement. The tubes are horizontal, in order to allow a vertical suspension, and the moving coils are placed astatically, one above and one below the inner tube. These are shown in the plane of the section instead of in the mean working position which is nearly perpendicular to the plane of the paper. This is done in order to show the shape of the coils, which are wound on ivory frames. They are held together by fine silver wires, one on either side of the inner tube, as indicated in the figure.

Phosphor-bronze strip suspensions are used, and two air damping vanes are provided. The damping boxes are of wood and are mounted directly on the outside copper tube. The instrument is read by telescope and scale.

Massive copper slabs placed parallel and 2.5 cm apart serve as current terminals. They are provided with five bolts so arranged that any number of parallel leads up to five may be connected symmetrically. These at the same time serve as supports for one end of the instrument, and the closed end is supported by an oak upright.

Water cooling is provided for the inside tube by passing water through it, but no special means are provided for cooling the outside tube.

While the very heavy copper slabs used for current terminals tend to equalize the stream lines in the larger tube about the

[3] For a detailed discussion of this principle and its application to electrodynamometers, see Agnew and Fitch, Elec. Rev. (Chicago) 60, p. 767; 1912.

axis as a line of symmetry, this was deemed insufficient for the most precise work. Accordingly a groove 5 cm wide was turned eccentrically in the large tube near the open end, so that the groove was 2 mm deep on the top of the tube and 3 mm deep on the bottom. When finally mounted a current was passed through the instrument and equipotential surfaces laid off on the tube. By a small amount of filing the eccentricity of the groove was adjusted, so that the equipotential surface was a plane perpendicular to the axis. It was found that the relation held very accurately throughout the length of the tube; that is to say, the distances between equipotential surfaces measured at different points on the circumference differed but 1 mm in 800.

From the principle of axial symmetry outlined above, it may easily be seen that no error due to skin effect in the closed end will enter. For this reason the moving coils were placed one-third of the length from this end, so as to minimize the effect of the leading-in cables, etc. Perhaps a fourth or even a fifth would have been better.

3. PERFORMANCE

It is of first importance to determine whether the instrument is affected by distribution errors. Rosa has described an indirect method for marking this determination by the use of capacity in the moving-coil circuit.[4] If the moving-coil circuit be short-circuited on a resistance shunted by a condenser having such a value that

$$L = C\,R^2$$

where L is the self-inductance, R the external resistance, and C the capacity shunted around it, then there should be no deflection on closing the circuit no matter what the position of the coil. But if there is such an error, then there will be a residual deflection.

When the instrument was first set up it showed no such error up to 300 cycles, but after it had been in service some time this same test showed a slight error. This was found to be due to a slight flexure of the inner tube, brought about by clamping

[4] This Bulletin, 3, p. 43; 1907. Reprint No. 48.

heavy cables and lugs to the massive terminals, and by differential thermal expansion. It was found that the trouble could be removed by slightly springing the inside tube. To get rid of the trouble the copper slab connected to the inner tube was cut in two and the two parts joined by means of a mercury contact. This gives a slight flexibility, enough to secure freedom from distortion of the inside tube. It is thus seen that a slight departure from the condition of axial symmetry introduces a distribution error; but this can easily be detected and corrected by a purely electrical test. Strong clamps and struts (shown in dotted lines in the figure) have been arranged to hold the copper slabs in proper position.

Measurements of large currents by means of a current transformer whose ratio had been carefully determined were in substantial agreement with the indications of the tubular dynamometer. It is believed that the instrument is accurate to 0.05 per cent.

It was found necessary to put loose-fitting diaphragms across the tube on each side of the moving coils to prevent air currents, for such currents of air caused considerable unsteadiness of the reading, even for comparatively small temperature differences in the mass of copper composing the instrument. The diaphragms effectually removed the trouble.

A more serious difficulty was encountered with magnetic impurities in the moving coil. The requirements here are even more exacting than in the sensitive moving-coil galvanometer, for the parts of the moving coils nearest the inside tube are in a field comparable in magnitude to the flux in the air gap in the permanent magnets of such galvanometers. The whole directive magnetic force exerted on the coil must be vanishingly small or the zero of the instrument will not be the same with current on that it is with current off. In the galvanometer, on the other hand, the requirement is merely that the magnetic force on the coil shall not vary appreciably through comparatively small angles.

Finally, special coils were wound by the Weston Electrical Instrument Co. which were entirely satisfactory. These were of

silver wire 0.2 mm in diameter, silk covered, and were stated by Mr. W. N. Goodwin, jr., of that company, to be actually diamagnetic.[5] They were mounted with great care, to prevent magnetic contamination from dust. The zero is precisely the same with current on or off.

At commercial frequencies no error whatever can be detected due to eddy currents being set up in the tubes by current in the moving system. Even with full load current of 900 cycles in the moving coils and with the field system short circuited, the deflection does not exceed 0.1 mm at any part of the scale.

It might have been better to have made the instrument with two independent sets of moving coils, one set for smaller currents, placed very close to the inside tube, where the field is strongest, perhaps even decreasing the diameter of the tube for the purpose, and a second set for heavier currents placed near the outer tube. This would extend the range of the instrument. In addition, current and power could be measured simultaneously.

4. CONSTANTS AND DIMENSIONS

Copper slabs for current terminals:	
Thickness	2. 5 cm.
Width	20 cm.
Outer tube:	
Length	101 cm.
Radii	6. 41 and 7. 07 cm.
Inner tube:	
Length	126 cm.
Radii	0.50 and 1.27 cm.
Total weight of instrument (approximately)	80 kg.
Moving coils:	
Diameters (approximately), 116 turns of 0.2-mm. silver wire	2. 5 and 5 cm.
Weight of each coil	7. 3 g.
Moment of inertia, each	12 g-cm.^{2}
Resistance—	
Coils alone	12. 2 ohms.
Total for system	14. 4 ohms.
Self inductance	1. 4 mh.

[5] Mr. Goodwin found the torque acting on the coils and tending to maintain them at right angles to a magnetic field having a strength of 1175 gausses to be 0.286 and 0.238 dyne-centimeters per radian, respectively.

Resistance:	
Outer tube	8 microhms.
Inner tube	56 microhms.
Complete instrument	67 microhms.
Power consumed (at 5000 amperes):	
Outer tube	200 watts.
Inner tube	1400 watts.
Complete instrument	1675 watts.
Magnetic field at center of coils (approximate)	300 gausses.
Sensitivity—100-cm deflection at 86-cm scale distance requires 100 amperes with 0.06 amperes in the moving coil.	
Capacity:	
With water cooling	5000 amp.
Without water cooling	1200 amp.
Of moving coil circuit	0.06 amp.

WASHINGTON, July 17, 1912.